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Directional Earth Fault Relay Operation in Mutually Coupled Multiple Circuit Distribution Lines

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***Abstract*—Many of the power utilities around the world have experienced spurious tripping of directional earth fault relays in their mesh distribution networks due to induced circulating currents. This circulating current is zero sequence and induced in the healthy circuit due to the zero sequence current flow resulting from a ground fault of a parallel circuit. This paper quantitatively discusses the effects of mutual coupling on earth fault protection of distribution systems. An actual spurious tripping event is analyzed to support the theory and to present options for improved resilience to spurious tripping.**

I. Introduction

In recent years, economic, environmental and right of way constraints have led many of the power utilities around the world to build number of unrelated circuits on the same physical pole structures. This is commonly seen when the circuits have the same physical path partly or entirely through their length. In distribution systems these two circuits can be of the same voltage or different voltages and usually built one underneath the other as super and sub circuits. These circuits may not be connected to the same substation at any given end.

The close proximity of these circuits produces sufficient mutual coupling between them. This effect is very well known in transmission line distance protection as “zero sequence mutual coupling” [1]. In traditional distance relay setting, the apparent impedance is altered by a factor to compensate for the zero sequence mutual impedance. There have been many papers [2]–[5] written on the subject of proper estimation of coupling effects for the accurate operation of the distance relay.

Protection systems of distribution systems with parallel circuits have experienced a slightly different problem to that of transmission line distance protection. However, the research work so far has been restricted to the transmission system ground distance protection relay, except for [6], [7], reporting on effects of mutual coupling on directional earth fault relays in transmission networks.

II. Positive, Negative and Zero Sequence Mutual Impedances of Transmission and Distribution Lines

For a single circuit transmission or distribution line, the following equation can be written for the voltage drops in the phases [8].

$$\begin{bmatrix} \Delta V_a \\ \Delta V_b \\ \Delta V_c \end{bmatrix} = \begin{bmatrix} Z_s & Z_m & Z_m \\ Z_m & Z_s & Z_m \\ Z_m & Z_m & Z_s \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{1}$$

where Z_s and Z_m are self impedance and mutual impedance of the line respectively. Here, it is assumed that conductors of three phases are the same and phases are properly transposed. This equation when converted to sequence components gives,

$$\begin{bmatrix} \Delta V_0 \\ \Delta V_1 \\ \Delta V_2 \end{bmatrix} = \begin{bmatrix} Z_s + 2Z_m & 0 & 0 \\ 0 & Z_s - Z_m & 0 \\ 0 & 0 & Z_s - Z_m \end{bmatrix} \times \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} \tag{2}$$

This shows that there is no coupling between different sequence components. However, in parallel circuits when lines are mutually coupled, sequence voltage drops of one line is affected by sequence currents flowing in the other line through respective sequence components. A quantitative study of these effects is presented in [9] challenging the common assumption to consider only the zero sequence mutual impedance ignoring the positive and negative sequence impedances. Nevertheless, the results in [9] show that the positive and negative sequence mutual impedances are very small for practical line constructions and can be ignored in most cases. Therefore, it is still right to say that all the mutual impedances between the two circuits are the same, if both the lines are properly transposed. If this mutual impedance is Z'_m, then the voltage drops of line 1 is given by

$$\begin{bmatrix} \Delta V_{a,1} \\ \Delta V_{b,1} \\ \Delta V_{c,1} \end{bmatrix} = \begin{bmatrix} Z_s & Z_m & Z_m \\ Z_m & Z_s & Z_m \\ Z_m & Z_m & Z_s \end{bmatrix} \begin{bmatrix} I_{a,1} \\ I_{b,1} \\ I_{c,1} \end{bmatrix} + \begin{bmatrix} Z'_m & Z'_m & Z'_m \\ Z'_m & Z'_m & Z'_m \\ Z'_m & Z'_m & Z'_m \end{bmatrix} \begin{bmatrix} I_{a,2} \\ I_{b,2} \\ I_{c,2} \end{bmatrix} \tag{3}$$

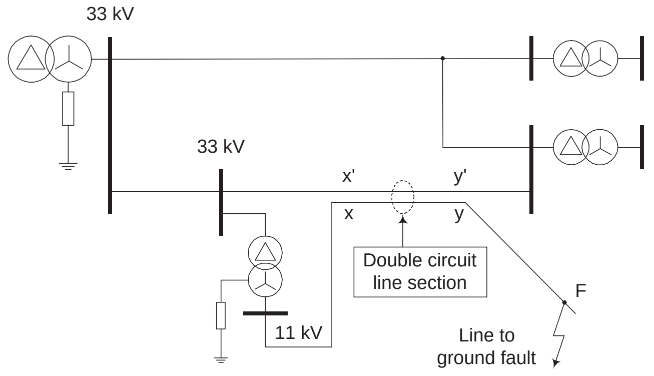


Fig. 1. A distribution system with parallel double circuit section

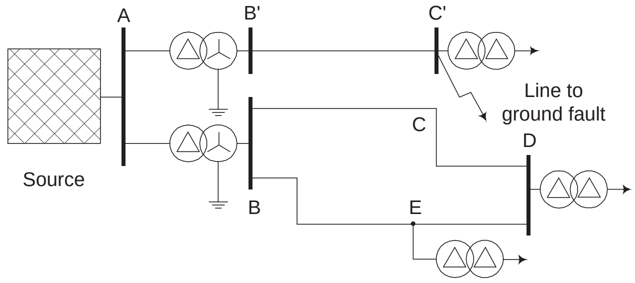


Fig. 2. Single line diagram of a 3-phase distribution system

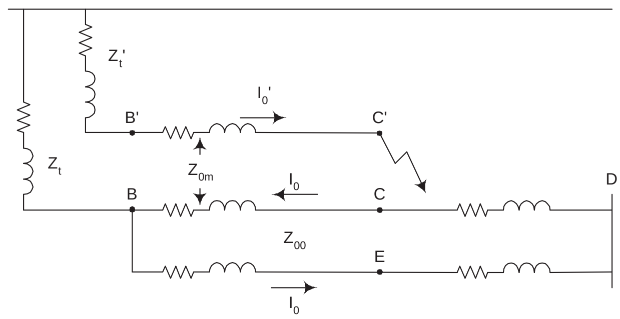


Fig. 3. Zero sequence network of the 3-phase distribution system

Applying sequence transformation, the following expression is obtained.

$$\begin{bmatrix} \Delta V_{0,1} \\ \Delta V_{1,1} \\ \Delta V_{2,1} \end{bmatrix} = \begin{bmatrix} Z_s + 2Z_m & 0 & 0 \\ 0 & Z_s - Z_m & 0 \\ 0 & 0 & Z_s - Z_m \end{bmatrix} \times \begin{bmatrix} I_{0,1} \\ I_{1,1} \\ I_{2,1} \end{bmatrix} + \begin{bmatrix} 3Z'_m & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} I_{0,2} \\ I_{1,2} \\ I_{2,2} \end{bmatrix} \tag{4}$$

This shows that mutual coupling between positive sequence networks and mutual coupling between negative sequence networks of parallel lines are zero. But mutual coupling between zero sequence networks is not zero. Hence, three-phase faults and line-to-line faults on one line will not affect the other parallel line. However, for all faults that involve ground, fault current in the faulty line will affect the performance of earth fault relays of the healthy line.

III. Earth Fault Operation due to Induced Circulating Currents

Fig. 1 shows a single line diagram of a section of a 33 kV distribution network. Here, there is a section where the 11 kV line is built on the same pole structures underneath the 33 kV line. The 33 kV lines form a simple loop as illustrated. For a single phase to earth fault at F, the zero sequence current flow in the 11 kV feeder will induce a zero sequence voltage in the parallel 33 kV line section via the mutual impedance between circuits. As there is a closed loop, zero sequence current will circulate in the 33 kV system. The magnitude of this circulating zero sequence current will depend on

- the magnitude of the earth fault current in the faulty line
- the mutual zero sequence impedance between circuits
- the zero sequence impedance of the loop

This zero sequence current will circulate in the loop even when the system is single point earthed as shown in Fig. 1. Multiple transformer neutral earth connections and the phase to earth capacitances of cables will provide additional current paths directly through the earth and affect the zero sequence current magnitude and phase angle at a particular relay connection point.

A. Induced Zero Sequence Currents in Ungrounded Distribution Loops

A single line diagram of a 3-phase distribution system and its zero sequence network are shown in Fig. 3 and 2 respectively . The sections of line BC and $B'C'$ are on the same poles; the only grounds in the system are those at the neutrals of the supply transformers. A line to ground fault occurs at C' causing the zero sequence current I'_0 to flow in the line $B'C'$ which induces a zero sequence voltage in the line BC. B will be at zero potential in the zero sequence network, but the zero sequence potential at C will be $I'_0 Z_{0m}$ where Z_{0m} is the mutual zero sequence impedance of line sections BC and $B'C'$. This voltage drop in the direction of I'_0 can be considered as a voltage rise in the direction CB. It forces a current I_0 to flow around the closed loop in the direction $CBED$. If the zero sequence impedance of the loop $CBEDC$ is Z_{00}, then the voltage drop in the loop is

$$I'_0 Z_{0m} - I_0 Z_{00} = 0 \tag{5}$$

Therefore induced zero sequence circulating current is

$$I_0 = \frac{Z_{0m}}{Z_{00}} I'_0 \tag{6}$$

Two of double circuit line constructions which are commonly used in practice are shown in Fig. 4 and 5. Zero sequence mutual impedance for construction types shown in Figs. 4 and 5 are $1.075\angle 82.08^o\,\Omega/\text{km}$ and $1.137\angle 82.52^o\,\Omega/\text{km}$ respectively. Self zero sequence impedances for two commonly used construction types are listed in Tables I and II. Simplified Carson's formulae given

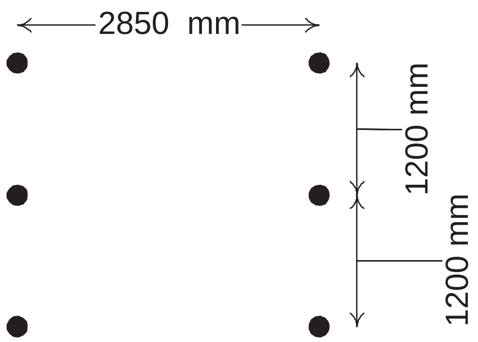


Fig. 4. 33 kV double circuit construction

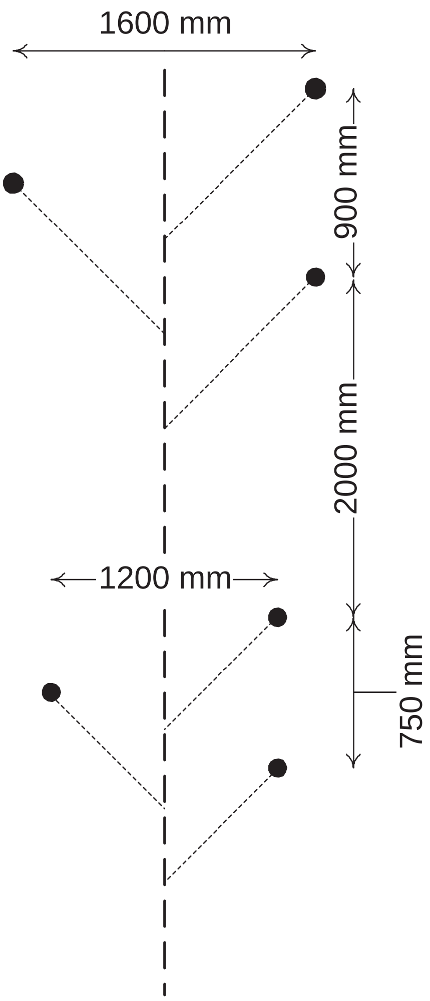


Fig. 5. 33 kV/11 kV double circuit construction

in [10] are used to calculate these values.

IV. A Real Spurious Tripping Event

A section of a 33 kV network of Energex, an Australian distribution utility supplying power to South East Queensland is shown in Fig. 6. Here the substation BDS is the source while the substation BDT is the weak in feed. The feeders F469 and F314 originating from BDS have a parallel section of 2.5 km. Feeders F469 and F468 form a simple loop network. Both feeders F469 and F468 are protected by a Permissive Overreach Transfer Trip (POTT) scheme using SEL 351 relays. POTT is a communication assisted protection scheme that is used to remove the fault quickly. In POTT scheme, relays at two ends of the feeder talk to each other through mirror bits on their respective decisions of the fault. Relays use local voltage and current measurements to decide whether the fault is in front of, i.e. “Forward” or behind, i.e. “Reverse” the relay. If both relays see the fault as “Forward”, then both relays trip causing the opening of breakers at both ends of the feeder, removing the fault within few milliseconds.

TABLE I
ZERO SEQUENCE IMPEDANCE FOR 33 KV VERTICAL OFFSET CONSTRUCTION

Conductor type	**Zero sequence impedance, Z_0 (Ω/km)**
AAC Libra	$1.148\angle 41.79^o$
AAC Mars	$0.961\angle 51.38^o$
AAC Moon	$0.854\angle 59.59^o$
AAC Pluto	$0.785\angle 66.27^o$
ACSR Raisin	$2.328\angle 19.48^o$
ACSR Apple	$1.292\angle 36.31^o$
ACSR Banana	$1.051\angle 45.62^o$

TABLE II
ZERO SEQUENCE IMPEDANCE FOR 33 KV VERTICAL DELTA CONSTRUCTION

Conductor type	**Zero sequence impedance, Z_0 (Ω/km)**
AAC Libra	$1.141\angle 41.37^o$
AAC Mars	$0.953\angle 50.96^o$
AAC Moon	$0.844\angle 59.21^o$
AAC Pluto	$0.775\angle 65.94^o$
ACSR Raisin	$2.325\angle 19.22^o$
ACSR Apple	$1.285\angle 35.91^o$
ACSR Banana	$1.043\angle 45.18^o$

SEL 351 relay uses the following expression [11] to estimate the zero sequence impedance.

$$Z_0 = \frac{Re\left[3V_0 \cdot (3I_0 \cdot 1\angle MTA)^*\right]}{|3I_0|^2} \tag{7}$$

where V_0 and I_0 are the measured zero sequence voltage and current at the relay and MTA is the zero sequence line angle setting of the relay which is typically set between 40^o and 90^o. The relay uses the following logic to determine the direction of the fault.

If $Z_0 < 1.25Z_{0F} - 0.25\left|\frac{V_0}{I_0}\right|$, then Direction = “Forward” where Z_{0F} is the forward threshold setting.

If $Z_0 > 0.75Z_{0R} + 0.25\left|\frac{V_0}{I_0}\right|$, then Direction = “Reverse” where Z_{0R} is the reverse threshold setting.

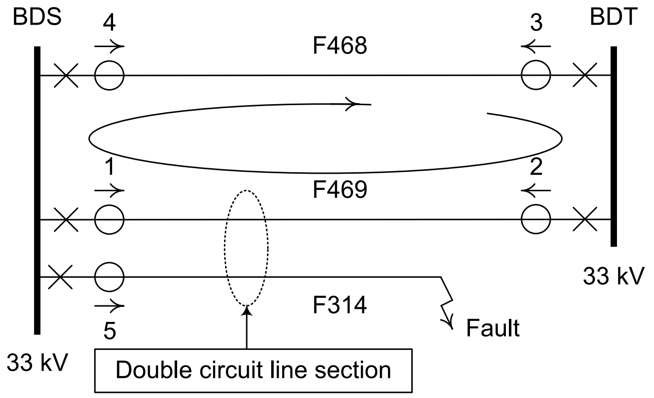
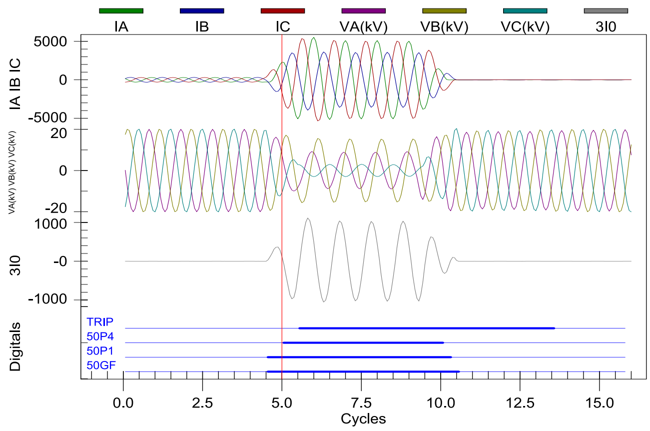
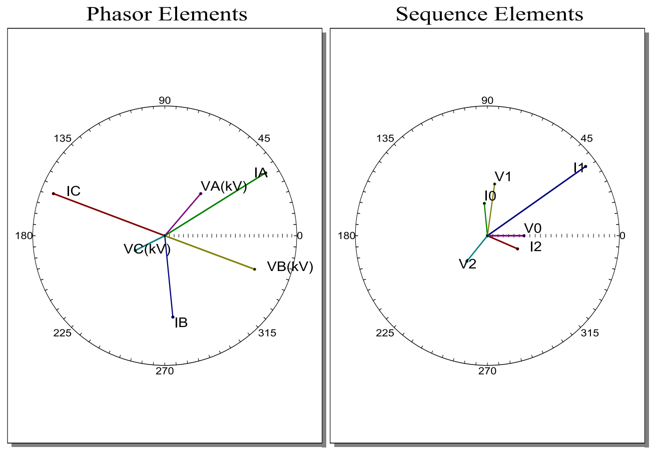


Fig. 6. A real 33 kV network with double circuit line section

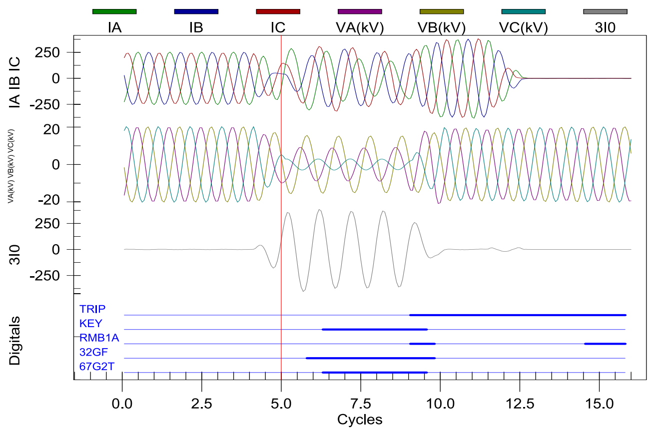


(a) Waveforms and logic signals

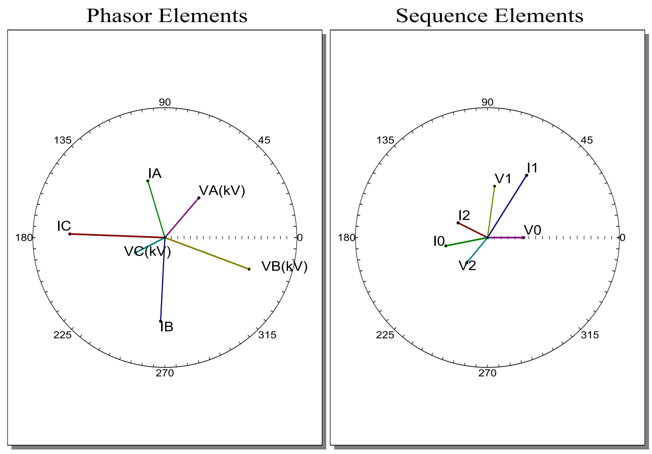


(b) Phasor diagrams

Fig. 7. Oscillogram obtained from relay 5



(a) Waveforms and logic signals



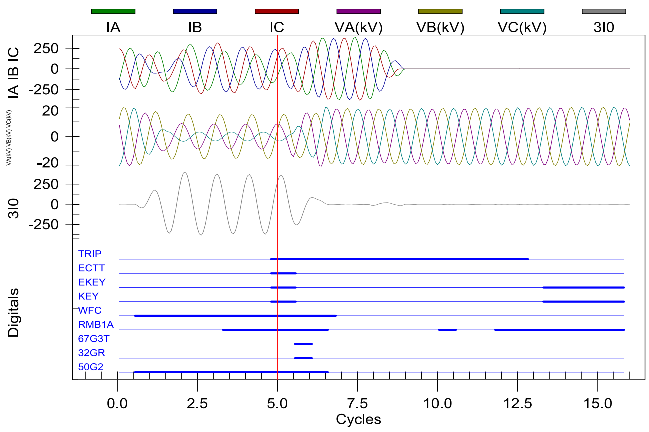
(b) Phasor diagrams

Fig. 8. Oscillogram obtained from relay 1

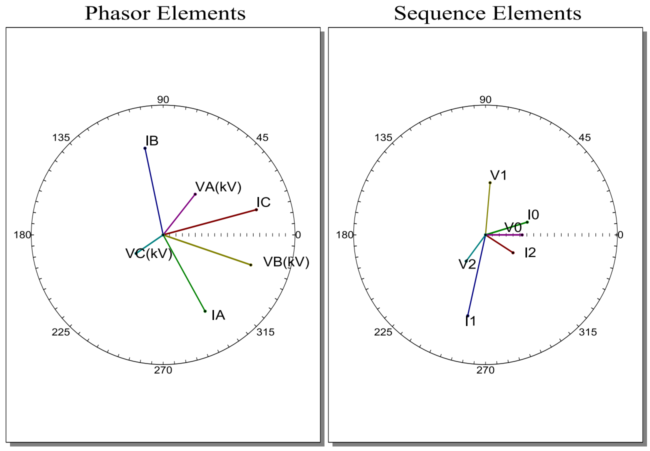
If $1.25Z_{0F} - 0.25\left|\frac{V_0}{I_0}\right| < Z_0 < 0.75Z_{0R} + 0.25\left|\frac{V_0}{I_0}\right|$, then the relay will not be able to make any decision on the direction of the fault.

Fig. 7(a) shows the waveforms of the F314, the faulty feeder from the BDS end relay. From the line current waveforms, it is very hard to determine the type of fault. However, flowing of zero sequence current suggests that it is a fault that involves ground. Phasor diagrams obtained from the same relay is shown in Fig. 7(b). This shows that the relay has recorded a zero sequence current of $340.6\angle 95.4^o$ A. The current angle is typical for a ground fault. The directional element of the relay has identified the direction of the fault without any difficulty and the fault is cleared approximately within 5 AC cycles. Here, the zero sequence line angle, MTA is set to 63.72^o for the relay. Figs. 8, 9 and 10 show the oscillograms obtained from relays 1, 2 and 4 respectively. There was no event recorded at relay 3. Magnitudes and phase angles of zero sequence currents recorded at 3 relays suggest that it is a circulating current in the direction shown in Fig. 6.

Although an angle greater than 95.4^o is expected as the angle of the induced zero sequence current measured at relay 2 according to (6), relay 2 has recorded a current of $126\angle 17.1^o$ A. The angle 17.1^o is quite unusual for a zero sequence current resulting from an earth fault and hence the directional logic of relay 2 was unable to determine the direction of the fault. This change of angle away from the expected value most likely would have been caused by the earth capacitances of cable sections. Here, all the relay directional elements are polarized to measure the currents in the forward direction.

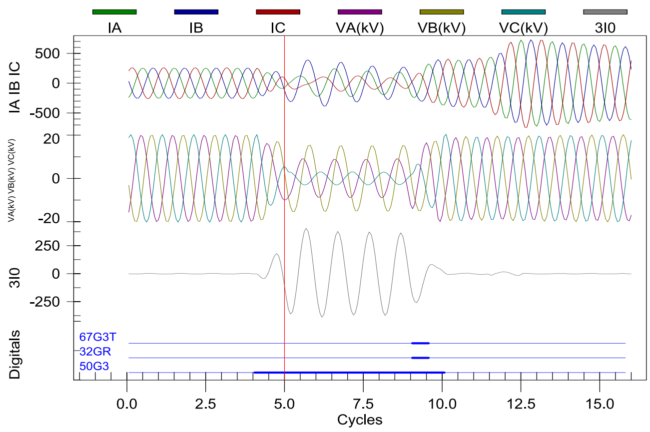


(a) Waveforms and logic signals

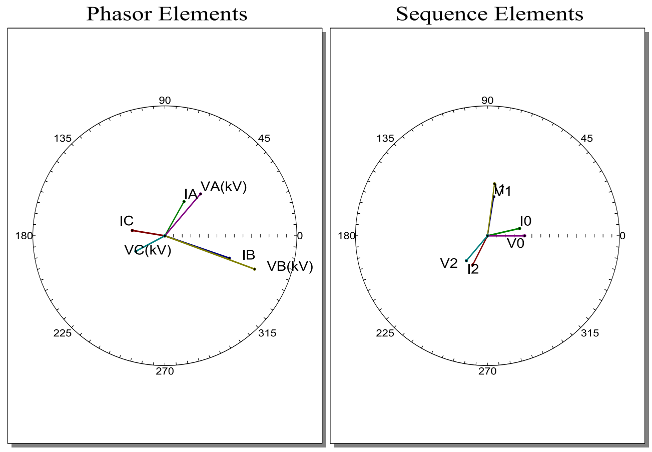


(b) Phasor diagrams

Fig. 9. Oscillogram obtained from relay 2



(a) Waveforms and logic signals



(b) Phasor diagrams

Fig. 10. Oscillogram obtained from relay 4

Relay 1 has recorded the current as $123\angle 191.5^o$ A while relay 4 has recorded it as $129\angle 13^o$ A. As these recorded magnitudes and angles are approximately equal, it confirms the presence of a circulating current. Relay 1 has recorded the fault as "Forward" while Relay 4 was unable to determine the direction. As Relay 2 was also unable to determine the direction of the circulating current, the tripping of relays occurred at both ends. In this case, Relay 2 misinterpreted the situation as 'weak in feed'. This is similar to an actual earth fault happening closer to BDS in feeder F469. Figs. 8 and 9 show that the circuit breakers at both ends opened removing the feeder F469 from service.

If all 4 relays identified the direction of the circulating current correctly, there would not have been a spurious tripping event. Moreover, this circulating current will only last until the fault in the parallel line is cleared.

V. Conclusion

This paper has discussed the effects of zero sequence mutual coupling of multiple circuit distribution lines and the probability of mutually induced zero sequence current to cause spurious tripping of directional earth fault relays of a healthy feeder. The mutually induced zero sequence current circulates in a loop network due to the zero sequence current resulting from a ground fault of a feeder in its close proximity.

In practical ground faults, this zero sequence circulating current can be large enough to be sensed by the ground fault relays in the loop network. A section of a real distribution network with a similar setting i.e. a healthy loop network with an adjacent feeder affected by an earth fault, has been analyzed here. Event records from the relevant relays were downloaded to obtain the oscillograms. Results of this spurious tripping event showed that the directional earth fault relays in the loop network interpreted the induced zero sequence current as an internal earth fault in one of the feeders instead of interpreting its actual circulating character.

According to the zero sequence mutual impedances of practical line constructions, the angle of the induced circulating current does not deviate to a greater extent from the angle of zero sequence current resulting from a true ground fault. However, in this case, it is observed that the angle of the circulating current is significantly different to that of the zero sequence current resulting from a ground fault. The reason for this change of angle is the additional current paths that directly go through the earth due to the phase to earth capacitances of cable sections. As a result, the directional elements misinterpreted the direction of the induced circulating current.

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